Primary Results of Xi’an Subsidence Monitoring by D-InSAR

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Outlines

- Research Background
- Main principles of Differential SAR Interferometry (D-InSAR) in subsidence monitoring
- Calculation procedure and key steps
- Main errors
- Test schedules and results discussion (Case of Xi’an city)
- Conclusions and some problems
Research Background

- World Famous City - Xi’an
## Serious geohazards

- **Long history of land subsidence in Xi’an:** from 1960’s up to date, including 5 evolution stages;
- **Large areas:** up to 1992, areas with cumulative subsidence of at least 100mm is over 105km², effect areas is over 200km² including 8 subsidence funnels;
- **Serious results:** the maximum subsidence is 1940mm, and the average subsidence rate is 80～126mm/year, the maximum was up to 300mm/year;
- **Land fissures:** 11。

<table>
<thead>
<tr>
<th>Stage Property</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Before 1970s</strong></td>
<td>1-3</td>
<td>70-90</td>
<td>More than 120</td>
<td>continuance</td>
<td>Slow down</td>
</tr>
<tr>
<td><strong>Remarks</strong></td>
<td>slowly</td>
<td>Become fast</td>
<td>Funnels</td>
<td>Large effect areas</td>
<td>Become slowly</td>
</tr>
</tbody>
</table>
The Cumulative Subsidence contour map in Xi’an during 1960-1992 (Yan, 1998)
tilt northwest over 1m of Dayan Pagoda
Research Project funded

- key project of Nature Science Fund of China (No: 40534021)
- the key project of the Ministry of Land & Resources, China (project No: 1212010440410)

Aims

- Calculating the subsidence evolution during 1992-2008
- Research the mechanism of subsidence
Main principles of D-InSAR

InSAR（Interferometric Synthetic Aperture Radar）

\[ \phi = \psi_1 - \psi_2 = \frac{4\pi}{\lambda} L_1 - \frac{4\pi}{\lambda} L_2 \]  

(1)

characteristics:
1. High precision (theoretically mm),
2. High spatial resolution (20m),
3. Large cover (100×100km²),
4. Low cost,
5. Need no GCP (ground control point)
\[ \phi = \psi_1 - \psi_2 \approx \frac{4\pi}{\lambda} B \parallel = \frac{4\pi}{\lambda} B \sin(\theta - \alpha) \] (2) \[ \phi_0 = \frac{4\pi}{\lambda} B \sin(\theta_0 - \alpha) \] (3)
Phase by height:

\[ \phi_{\text{flat}} = \phi - \phi_0 \approx \frac{4\pi}{\lambda} B \cos(\theta_0 - \alpha) \delta \theta = \frac{4\pi}{\lambda} B_\perp \delta \theta \]  

(4)

Height can be expressed as:

\[ h \approx L \delta \theta \cdot \sin \theta_0 = \frac{\lambda L \sin \theta_0}{4\pi B \cos(\theta_0 - \alpha)} \phi_{\text{flat}} \]  

(5)

Where Height ambiguity:

\[ h_{2\pi} = \frac{\lambda L \sin \theta_0}{2B \cos(\theta_0 - \alpha)} = \frac{\lambda L \sin \theta_0}{2B_\perp} \]  

(6)

(from tens meters to hundreds meters)
If deformation has occurred during two flights and the LOS deformation is $\Delta r$ showed as Fig. 3,

$$\phi_{\text{defo}} = \Delta \phi_{\text{flat}} = \frac{4\pi}{\lambda} \Delta r \quad (7)$$

Deformation ambiguity: $\Delta r_{2\pi} = \frac{\lambda}{2}$

So

$$\phi_{\text{flat}} \approx \frac{4\pi}{\lambda} \frac{B \cos(\theta_0 - \alpha)}{L \sin \theta_0} \frac{h}{\lambda} + \frac{4\pi}{\lambda} \Delta r \quad (8)$$
Three D-InSAR methods according to calculating DEM: (1) Two orbits + external DEM; (2) Three orbits with same master image; (3) Four orbits

\[ \Delta r_{Two} = \frac{\lambda}{4\pi} (\phi_{d+t} - \phi_{sim,t}) \]

\[ \Delta r_{Three, Four} = \frac{\lambda}{4\pi} (\phi_{d+t} - \frac{B^t_{d+t}}{B_t} \phi_t) \]
Calculation procedure and key steps

- SAR Image registration
- Interferogram calculation
- flat earth Subtracting
- topography(DEM) Subtracting
- Interferogram Filtering
- Unwrapping
- Geocoded-coordinate transformation
- Post processing-compensation and comparison
Main Errors of D-InSAR

\[ \phi = \phi_{geo} + \phi_{topo} + \phi_{atmos} + \phi_{defo} + \phi_{dem\_error} + \phi_{noise} \]

\[ \Phi_{defo} = 2n\pi + \phi_{defo} = W^{-1}\{\phi_{defo}\} \]

\[ C = C_{spatial} \cdot C_{temporal} \cdot C_{thermal} \cdot C_{registration} \cdot C_{doppler} \]

- Total phase
- Reference phase
- DEM phase
- Atmospheric delay
- Deformation phase (Information)
- DEM error
- Noise

- Unwrapping error
- Spatial Baseline decorrelation
- Temporal decorrelation
- Thermal noise
- Registration error
- Doppler deflection
Test schedules and results analysis

— — Case of Xi’an City (1992-1996)

Tab.1  SAR data

<table>
<thead>
<tr>
<th>N.o.</th>
<th>Track</th>
<th>Frame</th>
<th>Satellite</th>
<th>received date</th>
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<tr>
<td>1</td>
<td>390</td>
<td>2916</td>
<td>ERS-1</td>
<td>1992-07-03</td>
</tr>
<tr>
<td>2</td>
<td>390</td>
<td>2916</td>
<td>ERS-1</td>
<td>1992-08-07</td>
</tr>
<tr>
<td>3</td>
<td>390</td>
<td>2916</td>
<td>ERS-1</td>
<td>1992-09-11</td>
</tr>
<tr>
<td>4</td>
<td>390</td>
<td>2916</td>
<td>ERS-1</td>
<td>1993-01-29</td>
</tr>
<tr>
<td>5</td>
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<td>2916</td>
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<td>ERS-1</td>
<td>1993-04-09</td>
</tr>
<tr>
<td>7</td>
<td>390</td>
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<td>2916</td>
<td>ERS-1</td>
<td>1998-08-09</td>
</tr>
<tr>
<td>10</td>
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<td>2916</td>
<td>ERS-2</td>
<td>1996-07-01</td>
</tr>
<tr>
<td>11</td>
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<td>1998-08-10</td>
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<td>2913</td>
<td>Envisat</td>
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</tbody>
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Auxiliary data (1)

Landsat TM Image (Region of Interest)
ERS SAR SLC Image (Region of Interest)

Auxiliary data (2)
External DEM (from SRTM with 90m resolution)

High resolution DEM with 25m
• $20\text{km} \times 15\text{km ROI}$ (region of interest)
• Five schemes of test (Tab.2)
• Two orbits method
• High precise satellite orbit: DELFT orbit
• SRTM DEM(90m) and high resolution DEM(25m)

Tab.2 ERS SAR image with Track 390, Frame 2925

<table>
<thead>
<tr>
<th>Slave Items</th>
<th>19920807</th>
<th>19920911</th>
<th>19930129</th>
<th>19930305</th>
<th>19930409</th>
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<tbody>
<tr>
<td>Master</td>
<td>$B_{\parallel} \ B_{\perp} \ \Delta t$</td>
<td>$B_{\parallel} \ B_{\perp} \ \Delta t$</td>
<td>$B_{\parallel} \ B_{\perp} \ \Delta t$</td>
<td>$B_{\parallel} \ B_{\perp} \ \Delta t$</td>
<td>$B_{\parallel} \ B_{\perp} \ \Delta t$</td>
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<td>493 1173 70</td>
<td>167 385 245</td>
<td>469 1192 280</td>
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<tr>
<td>19920807</td>
<td>236 595 35</td>
<td>-178 -333 175</td>
<td>212 614 245</td>
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<td></td>
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<tr>
<td>19920911</td>
<td>-414 -928 140</td>
<td>-326 -788 175</td>
<td>Scheme 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19930129</td>
<td>Scheme 1</td>
<td>390 947 70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19930305</td>
<td>302 807 35</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Scheme 5</td>
<td>960107-960701</td>
<td>47 -37 175</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Scheme 1. 930129-0305 with 35 days intervals

Fusion image with 2.8cm/color cycle  \( Bt=140m \)
Scheme 2. 920703-930129 with 210ds intervals

Interferogram with 2.8cm/color cycle (Bt=245m)
Scheme 3. 920807-930305 with 210ds intervals

Interferogram with 2.8cm/color cycle \((Bt = -195m)\)
Scheme 3. deformation overlay map (using high resolution DEM)
Scheme 3. deformation overlay map (using high resolution DEM)
Scheme 3. Profile set
Scheme. 3 Profile X comparison with leveling data
Scheme. 3 Profile Y comparison with leveling data
Scheme 4. 920911-930409 with 210ds intervals

Interferogram with 2.8cm/color cycle (Bt = 19m)
Scheme. 4 deformation map (using SRTM DEM)
Scheme 4 deformation overlay map (using high resolution DEM)
Scheme 4 deformation overlay map (using high resolution DEM)
Scheme. 4 deformation overlay map (using high resolution DEM)
Scheme. 4 profile set
Scheme. 4 Profile X comparison with leveling data

- Residue
- Leveling
- D-InSAR

Land fissure
Scheme. 4 Profile Y comparison with leveling data
Scheme 4: pseudo subsidence due to unwrapping errors.
deformation map

Scheme 5 960107-960701 with 175 ds intervals
Some conclusions

- The results by using high resolution external DEM is better than that with the SRTM DEM in the two orbits D-InSAR processing.
- As for the monitoring of 1992-1993 deformation, 5-10 cm annual subsidence rate of most areas can be detected, while the maximum rate is up to 20 cm, and 3 funnels as Huijamiao, Fangyuan and Xiaozhai with over 13 cm can be clearly detected, which are consistent with the in-situ leveling data.
- Some relations between land subsidence and land fissure can be discovered by D-InSAR during 1992-1993.
- Average 7 cm/a subsidence rate in 1996 and the maximum is over 20 cm/a in the southern of city.
- By comparing the subsidence results between the year of 1992 and 1996, the magnitude lows down for the control of underground water withdrawal.

Some problems and further research consideration

- Unwrapping errors exist and optimal algorithm is needed especially in the condition of crossing land fissure.
- Interferogram filtering problem.
- Atmospheric effect is not researched.
- Time series method and PS technique are necessary to calculate the subsidence evolution over long time for the low coherence.
- Exact in-situ leveling data or GPS data should be collected to calibrate the D-InSAR results precisely.
THANK YOU!

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